Image Cover Sheet

CLASSIFICATION	SYSTEM NUMBER 180687
UNCLASSIFIED	

TITLE

BRAGG MIRRORS FOR FIBRE LASERS

System Number:

Patron Number:

Requester:

Notes:

DSIS Use only:

Deliver to:

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **01 AUG 1995**	2. REPORT TYPE	3. DATES COVERED **00-00-1995 to 00-00-1995**

4. TITLE AND SUBTITLE **Bragg Mirrors for Fibre Lasers**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Defence Research and Development Canada - Ottawa,3701 Carling Avenue,Ottawa, Ontario K1A 0Z4,**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This report describes the development of in-fiber Bragg gratings used as cavity mirrors for fiber lasers. The principal difficulty is to fabricate a 99 % total reflector and a 4 % output reflector with similar bandwidths and an identical operating wavelength. Photosensitivity at a light wavelength of 193 nm using an excimer laser and a zero-order-nulled phase mask was used to photoimprint the reflectors directly in Erbium-doped fiber. Two laser cavities were successfully fabricated and delivered to DREV. The long term resistance of the Bragg gratings to high light intensities in a Q-switched laser cavity looks promising.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**15**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Communications Research Centre
Centre de recherches sur les communications

3701 Carling Avenue
P.O. Box 11490, Station H
Ottawa, Ontario K2H 8S2

3701, avenue Carling
CP 11490, Succursale H
Ottawa (Ontario) K2H 8S2

FINAL REPORT

TITLE:
BRAGG MIRRORS FOR FIBRE LASERS

PROJECT OFFICER
Dr. Pierre Mathieu

PROJECT DIRECTOR
Dr. K.O. Hill

PROJECT CONTROL NO.
13/1-1993 (PRRN 25986)

SPONSORS
DREV, DRDCS

August 1, 1995

ABSTRACT

This report describes the development of in-fiber Bragg gratings used as cavity mirrors for fiber lasers. The principal difficulty is to fabricate a 99 % total reflector and a 4 % output reflector with similar bandwidths and an identical operating wavelength. Photosensitivity at a light wavelength of 193 nm using an excimer laser and a zero-order-nulled phase mask was used to photoimprint the reflectors directly in Erbium-doped fiber. Two laser cavities were successfully fabricated and delivered to DREV. The long term resistance of the Bragg gratings to high light intensities in a Q-switched laser cavity looks promising.

RESUME

Ce rapport décrit le développement de réseaux de Bragg photo-inscrits dans de la fibre dopée à l'Erbium afin de réaliser des miroirs utilisés dans des lasers à fibre optique. Le défi principal de ce travail est de fabriquer deux miroirs aux réflectivités très différentes, soit 4 % et 99 %, mais opérant à la même longueur d'onde et possédant une largeur de bande similaire. Ces miroirs furent photo-inscrits directement dans de la fibre à l'Erbium en utilisant un faisceau ultra-violet d'une longueur d'onde de 193 nm généré par un laser excimer, et d'un masque de phase dont l'ordre zéro est annulé. Deux cavités laser furent réalisées avec succès et livrées au CRDV. La résistance à long terme des réseaux de Bragg aux intenses puissances lumineuses produites dans un laser à fibre opérant en mode "Q-switched" s'avère prometteuse.

EXECUTIVE SUMMARY

Fiber lasers are being considered for use by the military in applications such as lidars, collision avoidance systems and through-the-air line-of-sight communications links. The fiber laser has the desirable attributes of being small and compact, yet capable of generating high power light pulses at 1550 nm (an eye safe wavelength). A key component in the development of efficient, compact fiber lasers is the mirrors used to form the laser cavity. This report describes the development of in-fiber Bragg gratings for use as reflectors in erbium doped fiber lasers operating at 1550 nm. The report discusses briefly the techniques used to fabricate Bragg gratings, the performance characteristics of the gratings, and their ruggedness. Two sets of Bragg grating reflectors were successfully fabricated and delivered to DREV for evaluation. The work also resulted in a capability to supply fiber Bragg grating reflectors to Marconi Canada for use in their collision avoidance system.

INTRODUCTION

In-fiber Bragg grating reflectors fabricated using fiber photosensitivity [1] are the ideal cavity mirrors for fiber lasers. The reflectors are photoinduced directly into the core of the optical fiber gain media or are fabricated in sections of fiber that are spliced onto the ends of the fiber gain media. In any case, the losses incurred in forming the fiber resonator cavity are low compared to other type reflectors as for example dielectric mirrors evaporated on the ends of a cleaved fiber. The cavity of a Q-switched fiber laser requires two reflectors, one with high reflectivity, the total reflector, and the other, the output reflector that has a low reflectivity. Both type mirrors can be fabricated using photosensitivity; the different reflectivities are obtained by controlling the length of the grating and the amplitude of the photoinduced grating. Another favorable attribute of in-fiber Bragg gratings is that the reflectivity is highly wavelength dependent. This characteristic is used to advantage in the construction of fiber lasers by designing a high reflectivity cavity mirror that has high reflectivity at the 1550 nm lasing wavelength and is transparent to light at the pump wavelength (980 nm or 1480 nm). Such a mirror eliminates the need for an intracavity coupler for coupling the pump light into the fiber gain media. The mirror reflection bandwidth of the Bragg grating is also much narrower than the bandwidth of the gain media. Thus the Bragg reflectors fix the oscillation wavelength during lasing. This characteristic is important for stabilizing the operation of Q-switched fiber lasers. This final report describes the development of Bragg grating reflectors of Er-doped fiber lasers. The report briefly describes the techniques used to fabricate the gratings, the performance characteristics of the gratings delivered to DREV and the ruggedness of the gratings.

FABRICATION TECHNIQUES

The fabrication of fiber Bragg gratings can be accomplished using several techniques [1,2,3,4]. At CRC, we have pioneered the use of KrF excimer laser [5] (operating at 249 nm) in combination with zero order nulled phase masks [3] for photoimprinting Bragg gratings in optical fibers. This method, which is now the preferred manufacturing technique for photoimprinting Bragg gratings, is the method that we used in this project for fabricating the Bragg gratings for the fiber lasers.

FIBER PHOTOSENSITIZATION

Some fibers such as conventional telecommunications fiber are not very photosensitive. In fact the photosensitivity in very few fibers is sufficiently strong to permit the fabrication of 99% reflectors for a grating length smaller than 1 cm. The photosensitivity of a fiber can be enhanced by using hydrogen loading [6] or flame brushing [7]. However, photosensitization using these techniques creates other problems. In the case of hydrogen loading, the resonant frequency of the photoimprinted grating drifts after fabrication due to diffusion of hydrogen out of the fiber [8] whereas flame brushing distorts the waveguiding properties of the section of fiber that is heated up to high temperatures. These deleterious side effects of photosensitization make it difficult to fabricate Bragg gratings having identical resonant wavelengths but with different reflectivities which is an important requirement on the Bragg gratings in this project.

Recently we have discovered that by irradiating the fiber with high intensity light at a wavelength of 193 nm large index changes can also be obtained [9] thus eliminating the need for photosensitization. It is this irradiation procedure that is used in the fabrication of the reflectors for the fiber lasers in this project.

ERBIUM DOPED FIBER TESTS

The erbium doped fiber used in Q-switched fiber lasers differs from that used in fiber amplifiers in that the dopant concentration for the erbium ion is much higher. The erbium fiber used in this work was obtained from the National Optics Institute. It has the following characteristics:

Table 1

Fiber ID:	406C6
Core diameter:	3.4μm
Confinement factor:	1
Core dopants:	Er/Al/Ge/P (Ge: 0.22 mole %)
Er concentration:	5300 $\pm$ 600 ppm-wt
Al concentration:	2.8 $\pm$ 0.3 wt%
Absorption:	37 dB/m @ 1535 nm 23 dB/m @ 980 nm
Attenuation:	33 dB/km @ 1200 nm
Numerical aperture:	0.2
LP_{11} cutoff wavelength (EIA,FOTP-80):	860 nm
MFD at 1539 nm:	6.6 μm
Half life time:	10.6 $\pm$ 0.1 ms
Deposited inner cladding:	SiO_2-P_2O_5-F_2 glass
Cladding diameter:	125 μm
Coating diameter:	180 μm

FABRICATION OF GRATING REFLECTORS WITH IDENTICAL RESONANT WAVELENGTHS AND DIFFERENT REFLECTIVITIES.

Phase I and II of the project consisted in the fabrication and characterization of a total reflector (>99%) and an output reflector (<4%) in an erbium-doped glass fiber. To ensure proper operation of the fiber laser, the resonant wavelengths of both grating reflectors forming the laser cavity should be identical. This requirement was the most difficult specification to meet in this project because the parameters used to control the mirror reflectivity also affect the resonant wavelength of the grating reflectors. Two approaches are possible to meet this requirement. In the first approach, the two reflectors that are photoimprinted in the optical fiber have the same length. The reflectivity of the grating is controlled through the strength of the photoinduced index modulation. Consequently, a 4% reflector will have a lower average index than a 99 % reflector. The bandwidth of the 4% reflector becomes smaller than that of the 99 % reflector. Also because the average index change is lower, the resonant wavelength of the 4% reflector grating is shifted to a shorter wavelength with respect to the resonant wavelength of the 99% reflector. This condition is unacceptable because it prevents lasing. To equalize the resonant wavelengths of the two grating reflectors forming the laser cavity, the 4% reflector is irradiated uniformly along its length with ultraviolet light. The uniform irradiation shifts the resonant wavelength of the 4% reflector without affecting its reflectivity.

In the second approach, the two reflectors are photoimprinted using the same irradiation exposure, i.e. both gratings have the same index modulation and thus identical resonant wavelengths. The reflectivity is now controlled by controlling the length of the grating. Consequently, the 4% grating reflector will be much shorter in length than the 99% reflector. In this case the bandwidth of the 4% reflector is larger than that of the 99% reflector.

In practice, two reflectors with widely different reflectivities, identical resonant wavelengths and similar bandwidths require the use of both of these approaches to obtain fiber Bragg gratings with the desired specifications.

Note that the use of a high intensity 193 nm irradiation source is required to carry out the above procedures for photoimprinting Bragg gratings without the use of any photosensitization. High intensity 193 nm photoinduces a high index change and yet avoids the wavelength shifting problems associated with H_2 loading.

FABRICATION OF LASER CAVITIES

Two fiber-laser cavities were fabricated consisting of Bragg gratings located at both ends of one meter of Er-doped fiber. The total reflector is specified to have reflectivity of 99% whereas the reflectivity of the output reflector is to be less than 4%. The Bragg grating reflectors were fabricated by exposing the erbium doped fiber to 193 nm irradiation through a phase mask. Two total reflectors were photoimprinted with lengths of 6 and 8 mm respectively using a 2 minute exposure of 193 nm irradiation at 50 pulse/sec with a fluence of about 200 mJ/cm^2. The output reflectors having a grating length of 0.9 mm were photoimprinted using similar irradiation conditions but an exposure time of only 25 sec. The resonant wavelength of the output grating reflectors was shifted to correspond to that of the total reflector using the technique of uniform ultraviolet light irradiation described previously. The matching of the resonant wavelengths of the total reflector and output reflector requires means for measuring the resonant wavelength of a Bragg reflector. This measurement is accomplished by measuring the spectral transmission of the Bragg grating. However, in the case of Bragg gratings in erbium doped fiber, the spectral transmission measurements are more difficult since the fiber is strongly absorbing (37 dB/m) at the wavelength (1534 nm) of interest. The Bragg grating reflectors were protected by applying a thin UV-curable coating. In the case of one fiber laser, serial number BR_L_1, the pigtail was too short to permit the application of an epoxy coating.

The characteristics of the two fiber laser cavities supplied to DREV are summarized in Tables I and II respectively. Note that the resonant wavelengths of the total reflector and the output reflector are matched within 0.1 nm.

Table 2

Fiber laser number	BR_L_1	
Mirror number	R1	R2
Center resonance (nm)	1534.6	1534.6
Linewidth FWHM (nm)	0.4	0.8
Reflectivity (%)	99	2.5
Grating length (mm)	8.0	0.9
Fiber type	Er-INO 406C6	
Pigtails length (cm)	2	10
Cavity length (m)	1	

Table 3

Fiber laser number	BR_L_3	
Mirror number	R1	R2
Center resonance (nm)	1534.4	1534.4
Linewidth FWHM (nm)	0.5	0.8
Reflectivity (%)	99	3.5
Grating length (mm)	6.0	0.9
Fiber type	Er-INO 406C6	
Pigtails length (cm)	10	10
Cavity length (m)	1	

BRAGG GRATING DURABILITY IN A HIGH INTENSITY LIGHT ENVIRONMENT

Bragg gratings can be designed to be rugged, that is the photoinduced index change is permanent and shows negligible deterioration at temperatures up to 100 °C. AT&T has studied the long term stability of fiber Bragg gratings photoimprinted in erbium-doped fibers and estimated that the grating should have a life time exceeding 20 years [10]. However, in the application of photoimprinted Bragg gratings in Q-switched fiber lasers, an unknown factor is the long term resistance of the gratings to the high light intensities in the Q-switched laser cavity. For a typical Q-switched laser having a peak output pulse of 100 W, the peak light intensity in fiber Bragg grating is approximately 1 GW per square cm.

The last phase of this project was to carry out tests on the resistance of the fiber Bragg gratings to high intensity light at the Bragg resonant wavelength. The plan was for DREV to carry out these tests. In practice, these tests are not easy to carry out since the deterioration if any is small. Several papers have reported on cw fiber lasers using fiber Bragg gratings [11, 12, 13]. Although the power level in these lasers is more than 1000 times smaller, no degradation in the Bragg reflectors has been detected. Furthermore, we have supplied fiber Bragg gratings to Canadian Marconi for use in their Q-switched fiber lasers[14]. These lasers generate light pulses at a peak power of 250 watts and at a pulse repetition rate of 3.5 KHz. Marconi has not reported any degradation in the fiber Bragg gratings in their Q-switched laser systems.

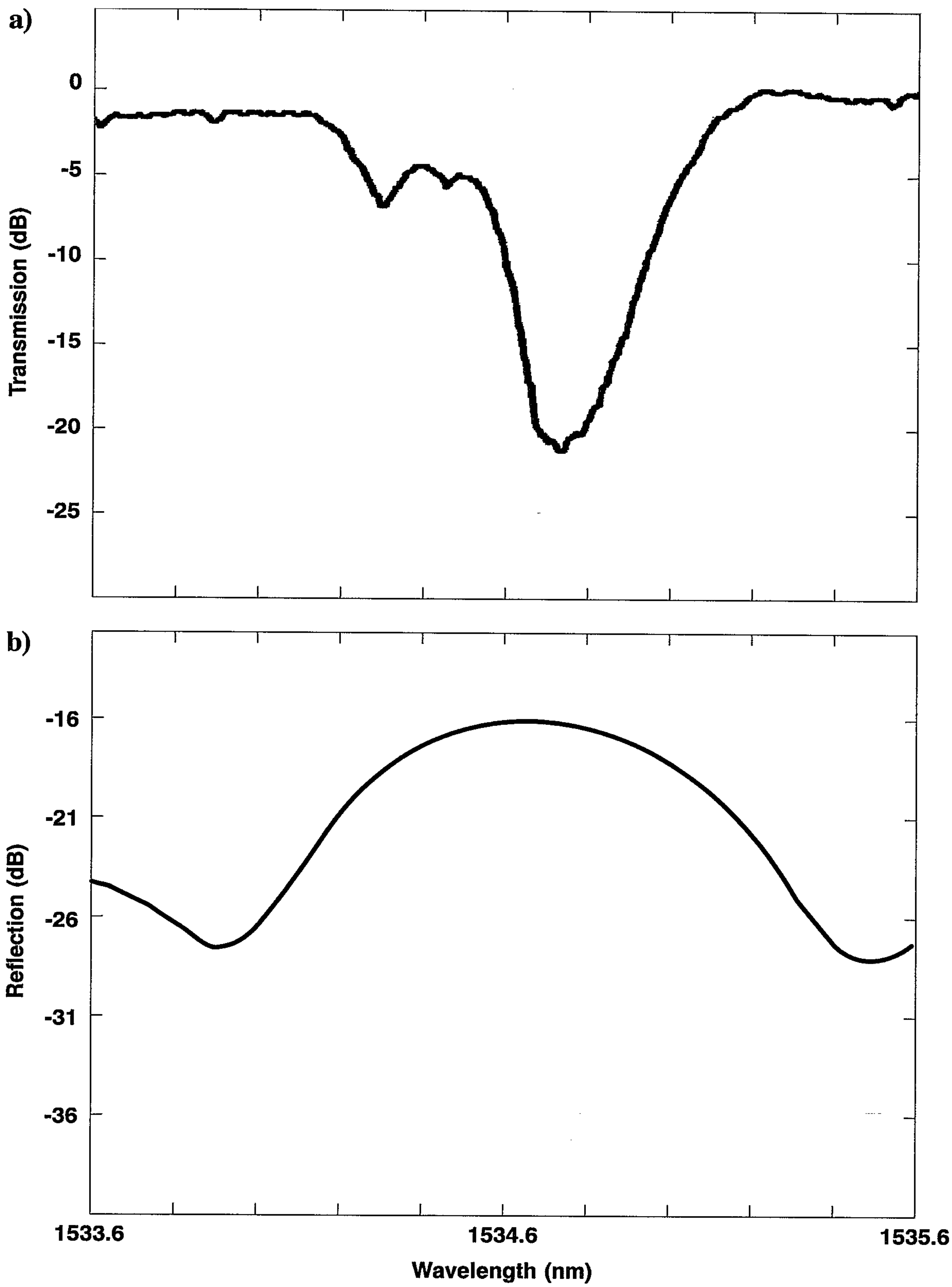

Fig 1 Fiber laser BR_L_1. a) transmission spectrum of total reflector R1 and b) reflection spectrum of output reflector R2.

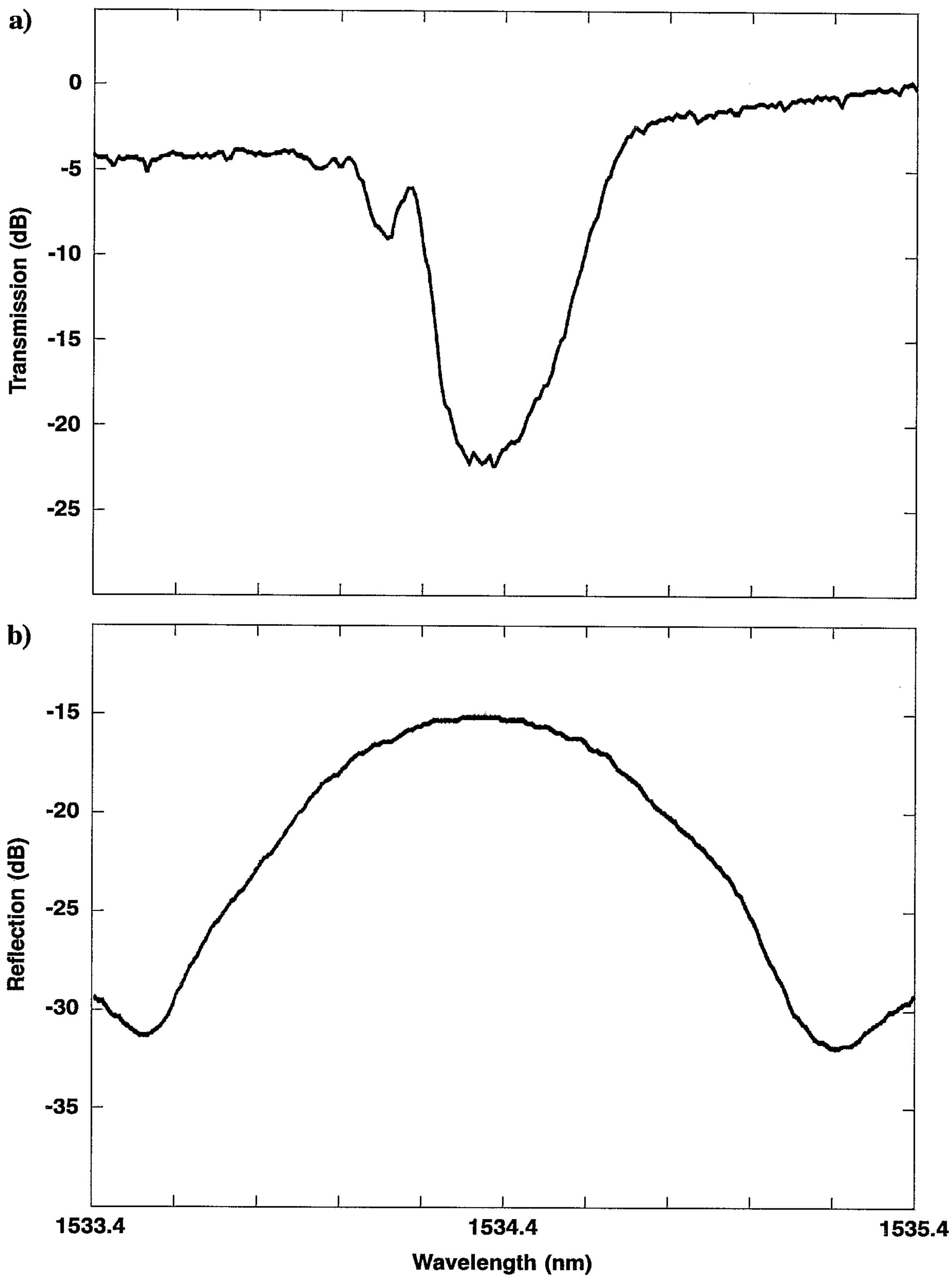

Fig 2 Fiber laser BR_L_3. a) transmission spectrum of total reflector R1 and b) reflection spectrum of output reflector R2.

REFERENCES

[1] K. O. Hill, Y. Fujii, D. C. Johnson and B. S. Kawasaki, "Photosensitivity in optical fiber waveguides: Application to reflection filter fabrication", Applied Physics Letters, Vol. 32, No. 10, pp. 647-649, May 15, 1978.

[2] G. Meltz, W. W. Morey, and W. H. Glenn, "Formation of Bragg gratings in optical fibers by a transverse holographic method", Optics Letters, Vol. 14, No. 15, pp. 823-825, August 1, 1989.

[3] K. O. Hill, B. Malo, F. Bilodeau, D. C. Johnson, and J. Albert, "Bragg gratings fabricated in monomode photosensitive optical fiber by UV exposure through a phase mask", Applied Physics Letters, Vol. 62, No. 10, pp. 1035-1037, March 8, 1993.

[4] B. Malo, K. O. Hill, F. Bilodeau, D. C. Johnson, and J. Albert, "Point-by-point fabrication of micro-Bragg gratings in photosensitive fibre using single excimer pulse refractive index modification techniques", Electronic Letters, Vol. 29, No. 18, pp. 1668-1669, September 2, 1993.

[5] K. O. Hill, B. Malo, K. A. Vineberg, F. Bilodeau, D. C. Johnson, and I. Skinner, "Efficient mode conversion in telecommunication fibre using externally written gratings", Electronics Letters, Vol. 26, No. 16, pp. 1270-1272, August 2, 1990.

[6] P. J. Lemaire, R. M. Atkins, V. Mizrahi and W. A. Reed, "High pressure H_2 loading as a technique for achieving ultrahigh UV photosensitivity and thermal sensitivity in GeO_2 doped optical fibres", Electronics Letters, Vol. 29, No. 13, pp. 1191-1193, June 24, 1993.

[7] F. Bilodeau, B. Malo, J. Albert, D. C. Johnson, K. O. Hill, Y. Hibino, M. Abe, and M. Kawachi, "Photosensitization of optical fiber and silica-on-silicon/silica waveguides", Optics Letters, Vol. 18, No. 12, pp. 953-955, June 15, 1993.

[8] B. Malo, J. Albert, K. O. Hill, F. Bilodeau, and D. C. Johnson, "Effective index drift from molecular hydrogen diffusion in hydrogen-loaded optical fibres and its effect on Bragg grating fabrication", Electronics Letters, Vol. 30, No. 5, pp. 442-444. March 3, 1994.

[9] J. Albert, B. Malo, F. Bilodeau, D. C. Johnson, K. O. Hill, Y. Hibino, and M. Kawachi, "Photosensitivity in Ge-doped silica optical waveguides and fibers using 193-nm light from an ArF excimer laser", Optics Letters, Vol. 19, No. 6, pp. 387-389, March 15, 1994.

[10] T. Erdogan, V. Mizrahi, P. J. Lemaire and D. Monroe, "Decay of ultraviolet-induced Bragg gratings", Journal of Applied Physics, Vol. 76, No. 1, pp. 73-80, July 1, 1994.

[11] G. A. Ball and W. H. Glenn, "Design of a single-mode linear-cavity erbium fiber laser

utilizing Bragg reflectors", Journal of Lightwave Technology, Vol. 10, No. 10, pp. 1338-1343, October, 1992.

[12] V. Mizrahi, D. J. DiGiovanni, R. M. Atkins, S. G. Grubb, Y.-K. Park and J.-M. P. Delavaux, "Stable single-mode erbium fiber-grating laser for digital communications", Journal of Lightwave Technology, Vol. 11, No. 12, pp. 2021-2025, December 1993.

[13] J. T. Kringlebotn, J.-L. Archambault, L. Reekie, J. E. Townsend, G. G. Vienne and D. N. Payne, "Highly-efficient, low-noise grating-feedback Er^{3+}:Yb^{3+} codoped fibre laser", Electronics Letters, Vol. 30, No. 12, pp. 972-973, June 9, 1994.

[14] T. Oleskevich and F. Séguin, "High-power Q-switched fiber laser", SPIE Vol. 2041, pp. 291-297, August 17-19, 1993.

180687